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INVESTIGATIONS OF PULSED DISCHARGES IN A DIELECTRIC CHANNEL WITH ABLATING WALLS

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INVESTIGATIONS OF PULSED DISCHARGES IN A DIELECTRIC CHANNEL WITH ABLATING WALLS

Yu. P. Rylov, et al.

ABSTRACT. Research was conducted on the volt-ampere characteristics of a pulsed discharge in a hollow cylindrical channel formed by walls of a dielectric. Measurements are made of erosion of the channel walls and average velocity of plasma flowing out into a vacuum through an aperture in one of the electrodes as a function of channel geometry. Inferences are made about plasma temperature and a mechanism of heat transfer to the wall.

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Symbols

d - channel diameter; l - channel length; C - condenser bank capacity; U - condenser bank charge; M - dielectric consumption in one discharge; m - specific consumption; W - discharge energy; R_0 - resistance of the discharge gap at the moment of maximum current; R - instantaneous channel resistance; I_m - maximum discharge current; W_1 - energy of breaking chemical bonds of dielectric mass M; W_2 - ionization energy of dielectric mass M; W_3 - kinetic energy of dielectric mass M; W_4 - energy of heating electrodes in one discharge; W_5 - thermal energy of dielectric mass M; T - average channel plasma temperature; S - light stream energy on the dielectric layer; h - depth of dielectric layer heated to temperature T; γ - dielectric density; c - specific dielectric thermal capacity; m_0 - mass of the dielectric layer heated to temperature T; T - temperature of the heated layer; k_1, k_2 - constants; u - residual charge.

Studies on discharges in channels bounded by dielectric walls are conducted in two directions: generation of a stable light source and plasma of relatively high temperature to $2 \cdot 10^4$°K [1] and obtaining a high-velocity stream of dielectric disintegration products [2].

Channel configuration differs corresponding to the different aims of these studies. In the first case short narrow dielectric channels were used having length l = 1 - 10 mm and diameter d = 1 - 2 mm; in the second case both dimensions were an order of magnitude higher.

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*Numbers in the margin indicate pagination in the foreign text.

In addition, the study of the interaction of plasma with dielectrics is of interest by itself and is important in production of heatproof coatings [3].

Therefore it is interesting to learn how plasma parameters change in a dielectric channel under increased duration and amplitude of a discharge current.

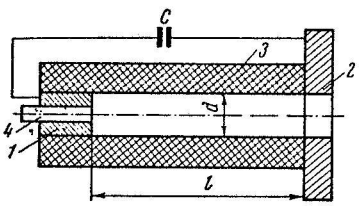

Figure 1.

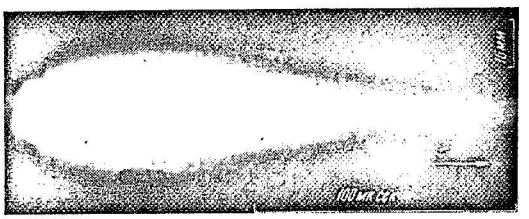

Figure 2.

The discharge gaps of the construction shown in Figure 1 have a channel of Teflon-4 with dimensions d = 9 mm, l = 200 mm and d = 16 mm, l = 30 - 165 mm. Discharge was triggered between electrodes *1* and *2* in the hollow cylindrical channel formed by the walls of dielectric *3*. A stream of plasma through the open end of the channel flowed into a vacuum. Discharge indication was accomplished with an auxilliary screen made by igniter structure *4*. Experiments in the 9 mm channel were conducted at a condenser bank capacity of C = 150 - 2,400 mfd, voltage U up to 5 kv (capacitors IM-5 - 150) and vacuum chamber pressure of 10^{-1} mm of mercury. At lower pressure the auxiliary screen energy (3 joules) was inadequate for reliable discharge indication. In experiments with the 16 mm diameter channel chamber pressure was 10^{-5} mm of mercury. An MBGV condenser bank was used with a capacity of C = 100 - 7,200 mfd at a voltage of U = 1 kv. Oscillographs were made of discharge current and voltage at the discharge gap; dielectric erosion of the channel wall was studied. Average velocity of the plasma stream flowing into the vacuum was calculated from the amount of measured motion of the plasma stream and consumption of the dielectric for one discharge. A cross section of the stream flowing out, shown in Figure 2, was taken with a spectrophotometer (gap crossways to the jet).

As discharge energy W is increased, consumption of teflon M for the discharge increases. In Figure 3 is shown the dependence of specific consumption /53

$m = M/W$ on W; the curves (and their associated points) are as follows: curve 1 for d = 9 mm and l = 200 mm, curves 2, 3 and 4 for d = 16 mm and values of l = 60, 115 and 165 mm respectively. For $W \geq$ 500 - 1,000 j., erosion of the walls is basically determined by channel geometry - by dimensions d and l. For $W <$ 500j., specific consumption also depends on W. An anomolous increase of m for W = 4.2 kj. is caused by incomplete disintegration of the dielectric because of thermal overloading of the channel and the face of the electrode, which led to its melting. In the table are given the values of residual voltage u kv on the condenser bank, maximum discharge current I_m ka and the relative value of energy of chemical breaking of bonds of the dielectric $w = W_1/W \cdot 100\%$ of mass M for condenser bank capacities of C = 150, 600, 1,200, and 2,400 mfd combined with a series of voltage values U kv on each bank.

In all experiments, condenser discharge was incomplete, and residual voltage grew with increased capacity as well as with increased initial voltage (see table). In Figure 4 the ohmic resistance value R_0 is given for the discharge channel at the moment of maximum current I_m as a function of W. The curves (and associated points) are: curve 1 and C = 150 mfd, U = 5 kv, d = 9 mm for l = 200 mm; curves 2, 3 and 4 for C = 100 - 7,200 mfd, U = 1 kv, d = 16 mm for l = 165, 115 and 65 mm respectively.

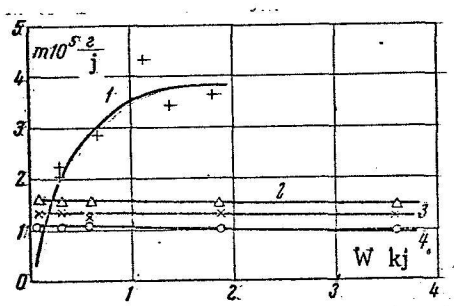

Figure 3.

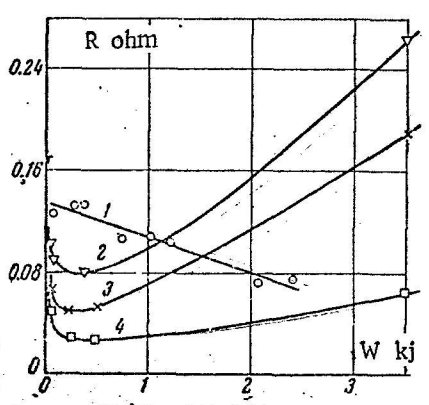

Figure 4.

C	150					600			1200		2400
U	1	2	3	4	5	1	2	3	1	2	2
u	0.2	0.38	0.67	1	1.15	0.1	0.93	1	0.34	1.4	1.77
I_m	6.23	11.6	20.8	28.6	44.4	6.54	15.2	27.3	5	13.1	—
w	15.2	52.4	67.6	103	87	49	66	92.6	95.3	81	754

Increasing voltage on the condenser bank without changing C leads to the linear decay of R_0; increasing C without changing voltage leads to an increase of R_0. This dependence of R_0 on the parameters of the discharge circuit (C and U) can be explained as follows. For small C = 150 - 600 mfd discharge duration is low, $\approx$ 60 μs and weakly dependent on U. As U increases, temperature and extent of channel plasma ionization increases, and consequently the discharge gap resistance decreases. Increasing C from 100 to 7,200 mfd (U = const) causes a substantial increase in discharge duration with a very mildly sloping discharge current front. With such a quasistable regime there occurs an intensive cooling by gas from the ablating wall and loss of temperature and plasma conductivity, with the result that discharge current decreases as C increases. Besides this, in such a regime, thermal drain is increased as a result of removal of energy with the exhausting stream in the course of the increasing discharge duration. For small C the exhausting process can be considered to take place after release of the main portion of energy in the channel. Figure 5 shows the dependence of discharge resistance on time (curves *1*, *2*), calculated from maximum current amplitude to $I = 0.1\ I_m$, and also current density (curves *1'*, *2'*) for C = 150 mfd. Curves *1* and *1'* are given for U = 4 kv, while curves *2* and *2'* are for U = 1 kv. Minimum R occurs at $I = (0.3 = 0.4)\ I_m$.

Evaluation of the average channel plasma temperature was made for discharges in which there was most probably complete dispersion of evaporated dielectric, i. e., in those instances where the energy spent on disrupting molecular bonds of the material eroded in one discharge was not greater than 0.5 W. /54 The following suppositions were employed: 1) the plasma is in thermodynamic balance; 2) the exitation energy of atoms and ions coming out of the chamber is extremely small.

The energy going into the channel is distributed between the energy reducing W_2, the energy disrupting molecular bonds W_1, the kinetic energy of the outflowing stream W_3, electrode heating energy W_4, and thermal energy W_5 according to the equation:

$$\int_0^\infty UIdt = W_1 + W_2 + W_3 + W_4 + W_5.$$

The Saha formula is used to approximate the solution of this equation. Mass of evaporated dielectric, average exhaust velocity, and energy losses in

the electrodes were determined experimentally. This means of evaluating temperature gave the following results:

$$\langle T\rangle = (2.3-2.5)\cdot 10^4\,^\circ\mathrm{K} \text{ for } W = 72\ \partial\,\mathrm{j} \text{ and } \langle T\rangle = (1.2-1.3)\cdot 10^4\,^\circ\mathrm{K} \text{ for } W = 290\ \partial\,\mathrm{j}.$$

In the initial period of discharge the result of instability of the temperature process can be somewhat higher than $\langle T \rangle$.

The radiation energy originating from $\langle T \rangle$ and the average particle density were calculated on the basis of optical transparency of the channel plasma from radiation curves of teflon plasma [4]. Good agreement was obtained between radiation energy and the energy expended on disruption of chemical bonds W_1. From this one can conclude in this case that radiation from the optically transparent plasma plays a substantial role in the mechanism of energy transmission from the discharge channel to the wall. For the 16 mm diameter channel, evaluation of the temperature by Spencer's conductivity formula, assuming even distribution of current in the channel cross section, gives $\langle T \rangle = 10^4\,^\circ$K. For narrow channels with small W values it leads to increased values of $\langle T \rangle \approx 7 \cdot 10^4\,^\circ$K. One can assume that in the narrow channel, inelastic atomelectron collisions have an effect on plasma conductivity.

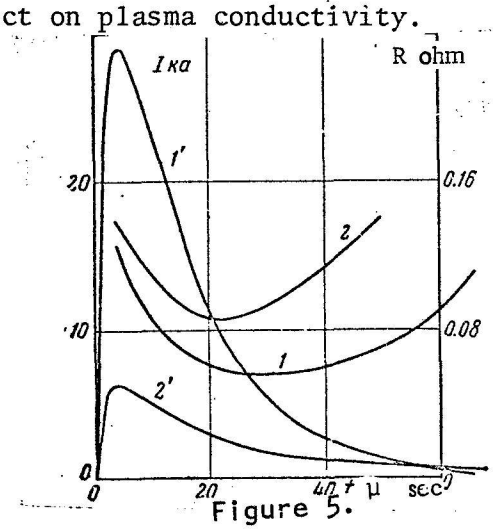

Figure 5.

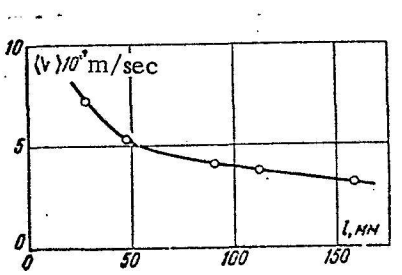

Figure 6.

As is known, absorption of light radiation by long molecules of the teflon deielectric type occurs in the surface layer to a specific depth. At low energy in the discharge this layer can increase its temperature by $\Delta T = \frac{S}{\pi h d l \gamma c}$.

Here S is light stream energy, γ is dielectric density, c is specific heat. With increased temperature loss of mass rapidly grows according to the Arrhenius formula for dielectric evaporation [5].

$$\frac{dm_0}{dt} = m_0 k_1 \exp(-k_2/T).$$

Here T is temperature of the layer, m_0 is mass of the heated layer, k_1 and k_2 are constants. This assertion explains why specific loss m is anomolously small at low energies.

It was learned experimentally that the amount of ablated material is not dependent on initial pressure in the channel within a pressure range of 10^{-1} to 10^{-5} m of mercury. This is explained by the fact that the length of the free path at these pressures is significantly higher than the characteristic channel dimensions.

Figure 6 shows the dependence of average exhaust velocity on discharge channel length. For $l \geqslant 50$ mm, velocity is weakly dependent on channel length, as evidenced by the purely gasdynamic character of forces for large channel lengths and the presence of electrodynamic action for small ones. Based on equations of unstable flow of gas out of tubes of constant cross section, one can show that velocity values correspond to calculated temperature values [6]. Calculation of average exhaust values was made according to the formula /55

$$\langle v \rangle = \zeta \sqrt{2E/M}.$$

Here E is the energy of ablation product heating, M is mass of evaporated material, ζ is a coefficient dependent on gas composition. Maximum velocity of the exhaust front was determined by spectrophotometry, and as a rule was 4 to 5 times greater than the average velocity. Its theoretical evaluation was made by the following formula from [6]

$$v_{\max} = \frac{2}{k-1} c_0.$$

(Here k is the ratio of specific heat, c_0 is the speed of sound in the undisturbed gas). This gave satisfactory agreement with the experiment.

As long as the channel shape remained nearly cylindrical during an extended work period, one could assume that the presence of hydrodynamic flow along the channel had no serious effect, but this question needs further study.

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